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CONTRACTOR FINAL REPORT NO. Serial S0304

AUTONOMOUS UNDERWATER VEHICLE
ARRAY DEPLOYMENT SYSTEM
PHASE I FEASIBILITY STUDY

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BERNARD BISHOP
PRODUCT PLANNING INC
MARCH 1990

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY

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AUTONOMOUS UNDERWATER VEHICLE
ARRAY DEPLOYMENT SYSTEM
PHASE I FEASIBILITY STUDY

Submitted by

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20 March 1990

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TECHNICAL ABSTRACT

➤ The purpose of this research is to investigate the feasibility of stowing a cable/array internally on a fixed drum and to explore the application of linear drive principles for the primary drive.

The application of a fixed drum stowage reel with linear capstan techniques would minimize a cable/array deployment system's size and weight. This optimization of size and weight could make array deployment from a tethered torpedo or autonomous underwater vehicle possible, without high fuel consumption. The fixed stowage reel could be an existing torpedo structure with no weight increase. The linear capstan could weigh twenty pounds or less (plus motor). Its operational capability would only be limited by torpedo power to overcome array drag and supply motor torque. The linear capstan is a torque balanced, closed loop device capable of pushing an array into stowage, while coincidentally retrieving the array under tow tension.

This study includes tests which manually wrap hose in a container to study level wind quality and repeatability. Linear drive tests include the manufacturability of internal guide cams. In addition, a high helix linear drive output was verified by physical measurement of travel versus calculated projections.

IDENTIFIERS/KEY WORDS

Keywords:

AUV Array Deployment; Cable Handling System; Internal Drum Cable Stowage; Fixed Drum Cable Stowage; Linear Capstan; (K7) 4

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PHASE I STUDY

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AUTONOMOUS UNDERWATER VEHICLE ARRAY DEPLOYMENT SYSTEM

1.0 PROJECT SUMMARY

The purpose of this research is to investigate the feasibility of stowing an array internally on a fixed drum and to explore the application of linear drive principles for the primary drive.

The objective of our study was to gain insight on fixed drum cable stowage limitations in order to project size and applicability of a linear drive. The fixed drum method of cable/array handling offers many advantages for autonomous underwater vehicle (AUV) applications. A linear drive being cylindrical in shape and light in weight is an ideal configuration for AUV design. A fixed drum stowage reel would not require addition to, nor modification of the AUV structure, since the reel is the structure.

To prove the feasibility of internal drum stowage, we formulated our Phase I study with two technical objectives. First, to gather technical information to determine the state-of-the-art and define the most probable cable/array diameter and lengths. Second, to perform material and component tests to project design limitations for this linear drive application.

We attempted to define array size by conducting a database search, as well as making phone contacts and meeting with AUV system designers. System definition was concluded with design calculations. Since no contact or paper suggested potential array diameter or scope, calculations were based on our cable/array size estimates.

We next defined limitations of a stowage design solution using critical item testing. These tests were of an observation type where assumed array simulations were evaluated for stowage characteristics and limitations.

Testing was divided into two groups: a) determination and verification of physical factors necessary for natural internal drum stowage; and b) verification of a linear drive size and its designability. Test conclusions were positive.

- o Internal drum cable/array stowage is probable utilizing natural array torsional and longitudinal characteristics.
- o Cable/array wrap factors such as torsional regulation and push force are within linear drive capability.

- o External system factors such as stowage size, friction etc., are drive and structure design controllable.
- o Static level winding is probable, depending on the length and size of cable/array deployed.

The Phase I proposed system weight goal was 50 pounds. Our 6 inch diameter model weighs less than 20 pounds. Our Phase I goal to gain understanding of parameters affecting orderly stowage, using 50 feet of hose in a fixed drum, was successful.

There are a number of unique benefits from an autonomous underwater vehicle array deployment system. The first to be considered are those requiring accuracy of position or personal safety. A tethered torpedo could be used as a communications or surveillance device for surface ships and submarines. The separation of a listener from ship's noise or at different thermoclines could prove most useful for submarines. This system approach could also be applicable to the oil and gas industries for data logging, or for air refueling hose pods.

2.0 RESEARCH OBJECTIVES

The objective of this research is to investigate the feasibility of internal drum cable/array stowage. We believe that this next generation system is possible today, because of recent *Product Planning Inc* capstan concepts in combination with previously employed cable handling techniques.

This system approach would functionally provide a means to gather underwater data in hazardous areas and/or at various thermoclines. Along with this functional advance, we would expect operational likelihood because of the linear drive's small diameter to length ratio, low weight, ability to push the fixed end of a cable/array while pulling the free end, and its ability to control torsion.

Our approach to extend underwater cable handling to autonomous vehicles has great potential. This method of cable handling would employ a capstan of extremely low weight and size to maintain torsional and longitudinal force for stowing cable/array independent of retrieval force. To accomplish this mode of operation, a linear drive would have to be designed to match the natural torsional and tensile qualities of a specific cable/array.

The linear drive inherently could push the cable at the stowage side with the cable helically buckled for stowage, while pulling the cable at the tow point. The combination of both these capstan design elements by one mechanism is necessary to minimize cable/array stress levels. The stowage drum may be the unmodified AUV structure, which simplifies design and minimizes weight.

To investigate the feasibility of this concept, we formulated our Phase I study with two technical objectives. First, to gather technical information to define a probable cable/array diameter and length. Second, to perform material and component tests to define the limitations of our solution.

3.0 RESEARCH APPROACH

Defining the extent of the problem is the single most important design element necessary for design success, yet it is the first to be overlooked. To succeed, the system designer must understand all the implications of the design before he can formulate the operational system. There must be a complete understanding of design limitations prior to committing to capability.

To increase our understanding of problem scope, we employed conventional pre-developmental research methods. Our study started with a Defense Technical Information Center (DTIC) database search. We then made phone contacts and setup a meeting with AUV system designers. Our data search was concluded by linear drive exploratory calculations and mathematical modeling with a focus on problem magnitude. Various stowage methods and simulated cable/array types were reviewed by test to better understand the extent of the problem, as well as the limitations of our proposed solution.

In addition to our field status review, critical item testing was performed to prove concept feasibility. Pre-contract system designs were first evaluated to estimate the operating parameters of a linear drive model. Previous designs were not directly applicable with the major difference being the need to double the drive's helix angle as compared to that previously achieved.

The first critical test for our Phase I study was to determine if a cable/array is internal drum stowable and what are the major factors controlling design. These tests were conducted as a worst case situation investigating simulated array material and construction.

The next tests scheduled were to verify if a high helix angle linear drive could be manufactured using previous techniques. The drive evaluation did prove fruitful in that it uncovered some manufacturing restrictions.

Our final investigation was to verify if a high helix angle capstan model was designable. This was accomplished by verification tests where a 5/8 inch diameter rod was used to simulate an array to verify if measured response was equivalent to calculated response.

Our research of internal drum stowage methods and our critical item testing of a drive model indicate internal drum stowage may be possible and is probable. Our field review highlighted high interest, if not need, for a system of our type. And our test conclusions gave us the confidence to commit to a design approach that may solve this need and continue into Phases II and III.

4.0 RESEARCH RESULTS

The measurement and understanding of naturally laying cable/array onto or in a drum is critical to designing the optimum AUV array deployment system. System operation depends on two elements; how the cable naturally responds when stowed, and can a drive be designed to anticipate this response. We decided it important to study both the ENLINE™ Capstan torsional/longitudinal control and the possibility of manufacturing such a device. Understanding the major limiting factors of internal fixed drum stowage has given us the confidence necessary to pursue Phase II design.

The Phase I test program was set up to investigate various aspects of hose stowage control. First, to study and determine the effect of simulated cable/array geometry and material. Second, to study the ENLINE™ Capstan model and assure we could extend previous design to a high helix angle drive design. In addition, we were interested in proving that drive size and weight are low enough to consider for an AUV application.

4.1 TECHNICAL BACKGROUND STUDY

A cursory technical review was performed to define the state-of-the-art of AUV cable handling. Our primary interest was to establish cable/array diameter and scope. Our technical review included two approaches. First, a DTIC search for published technical papers. Second, a searching out of end users to establish today's design direction. These reviews were limited by budgeted time constraints as per our Phase I proposal and are not meant to be all inclusive.

4.1.1 PUBLISHED PAPER SEARCH

The DTIC technical search located nine papers that indicated recent AUV development. In general, the main topic matter in these papers concerned propulsion limitations. These papers did reinforce our concerns to minimize system size, weight and tow cable drag. None of the papers had referenced an AUV as an array towing platform.

4.1.2 END USER SEARCH

Various agencies were contacted and notices published in order to locate end users and determine current design

art. News articles were published by the U.S. Military Robotics Newsletter and Unmanned Systems Magazine giving notice of this Office of Naval Research (ONR) contract.

Phone contact was made with the following Government and civilian agencies in hopes to determine potential array size and scope. Agencies we felt were interested included Office of Naval Research (contracted); Naval Underwater Systems Center (NUSC, Newport); Naval Sea Systems Command (NAVSEA); Defense Advanced Research Projects Agency (DARPA); Unisys Corporation; and Martin Marietta.

A meeting was held with Unisys Corporation's AUV designers at *Product Planning Inc* to review our facility and contract direction. We believe that all the aforementioned parties are interested in AUV cable handling, but would not commit to their immediate position nor direction. In no case, did any source indicate that array deployment from a torpedo is being considered, nor what cable/array size would be probable if attempted. We believe there is a potential for Phase III support because of the high response during a very short time period.

4.2. HOSE STOWAGE TESTS

It is most important to understand the effects of both array geometry/material and stowage drum geometry. Our main interest was to define those primary factors which would help and hinder internal drum stowage. Visual performance tests were conducted using a variety of simulated drum shapes with various simulated array materials. Hose was used for most tests to represent a scaled down version of a Thin Line array. The 3/16 inch diameter cable was considered to represent an oversize fiber optic cable/array.

Materials for Simulated Arrays

- o 3/16" x 1/4" Dia, 7 x 19 Galv, PVC Coated Cable
- o 1/2" Diameter, 3 Strand Nylon Rope
- o 3/4" OD x 1/16" Wall Tygon Tube
- o 5/8" OD x 1/16" Wall Tygon Tube
- o 1/2" OD x 1/16" Wall Tygon Tube
- o 3/8" OD x 1/16" Wall Tygon Tube
- o 3/4" OD x 1/8" Rubber Garden Hose
- o .64" OD x 1/16" Nylon Reinforced Hose

Materials for Simulated Stowage Drum

- o 10" Dia Base x 2" Wall x 12" High PE Pail
- o 9" Dia Base x 9" Wall x 10" High Galv Pail
- o 10" Dia x 16" High Glass Water Bottle
- o 9" Dia x 16" High Glass Mason Bottle

The following internal drum stowage observations were made visually by testing the above combinations of simulated arrays and drums.

4.2.1 TORSIONAL AND LONGITUDINAL STIFFNESS

Cable/array stiffness is the primary factor in determining good internal drum wrapping. The array must have enough stiffness to self support itself in an arched shape to resist gravity and forces due to acceleration. This can be aided by a torsional component but the stiffer the array, the easier to wrap a natural spiral. Along the same lines, damaged sections such as kinks or hockles effect or prevent a good level wind. When the 3/4 inch diameter tygon tubing was tested, it would not wrap with the drum vertical or horizontal partially because of kinks and flatness. By inserting the nylon rope, the hose was stowable with the drum vertical. The horizontal wrap was also possible but not with as good a level wind. Torsional and longitudinal (push) force can be programmed into the linear drive to control wrap.

4.2.2 SURFACE FRICTION

The surface friction of the simulated arrays varied greatly. The lower friction material combinations stowed the best. To assure friction was the factor being witnessed, we wet the larger diameter tygon tube which immediately improved the level wind. Tygon was the worst case combination (highest friction). If an existing structure is used for the reel, teflon wear strips could be added at structure contact points to reduce friction.

4.2.3 STOWAGE DRUM DIAMETER

Optimum drum diameter should be determined by array diameter and stiffness. For the drum sizes tested, the smaller diameter simulated arrays had a more consistent level wind. The wire cable was most controllable and the 3/4 inch diameter tygon tube the least controllable. The linear drive would be designed to match the stowage drum and array size to optimize stowage stress.

4.2.4 GRAVITY AND LEVEL WINDING

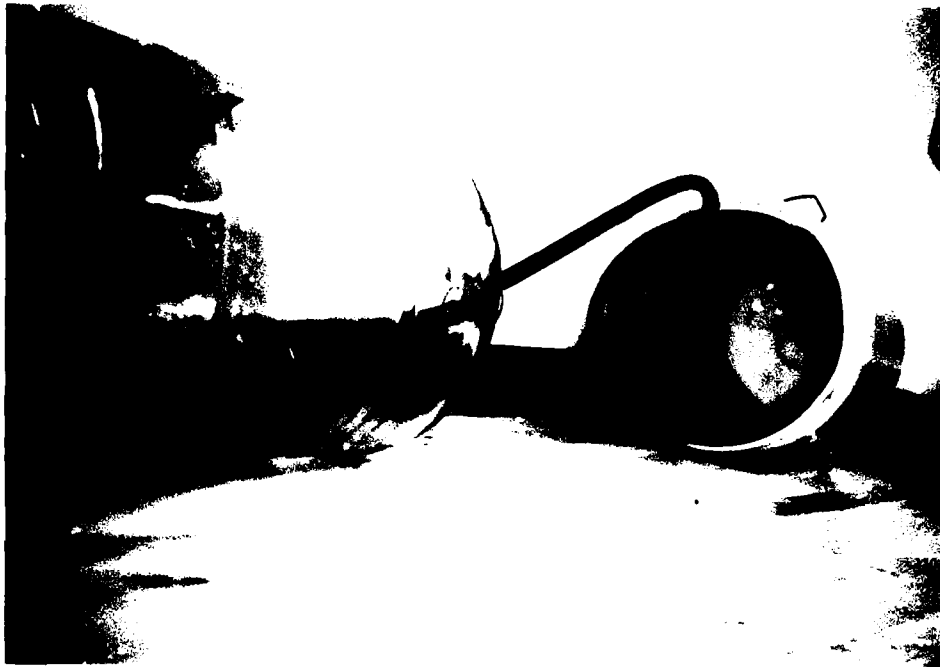
Gravity does effect the neatness of wrap, with vertical level winding the easiest to perform. Gravitational force could be minimized by using the linear drive to overcome gravity while laying up the array. Level winding is also an asset. The funnel action of the water bottle was a very effective static level wind.

4.2.5 QUALITY OF LEVEL WIND

Many of our horizontal tests used a pail to contain the hose being stowed in a five gallon water bottle, as shown in Photo 4.2.5A. The pail and inline pushing of the hose into the bottle neck roughly duplicates the action of the linear drive.

These tests were performed by first pushing the random coil of hose from the pail straight into the neck of the bottle. The hose was then returned in a similar manner into the pail. This was done repeatedly to check for

When a product is designed, it is often necessary to test it under conditions that simulate the actual use of the product. This is done to ensure that the product is safe, reliable, and meets the needs of the user. One common test is to simulate the conditions of use in a laboratory setting. This can be done by using a test setup that replicates the conditions of use. For example, a test setup for a hose might involve a hose connected to a pump and a nozzle, with the hose being tested under various conditions of use.



4.2.5A HOSE STOWAGE TEST SETUP



4.2.5B LEVEL WIND QUALITY

When a final outer wrap in the bottle was achieved, the coiling would continue forming a semi-elliptical coil inside the previous layers while still maintaining a circular open loop. This may be a strong indication that multiple wraps are possible. Photo 4.2.5C was taken from the bottom of the bottle and shows the neat and consistent open pattern of hose wrap.

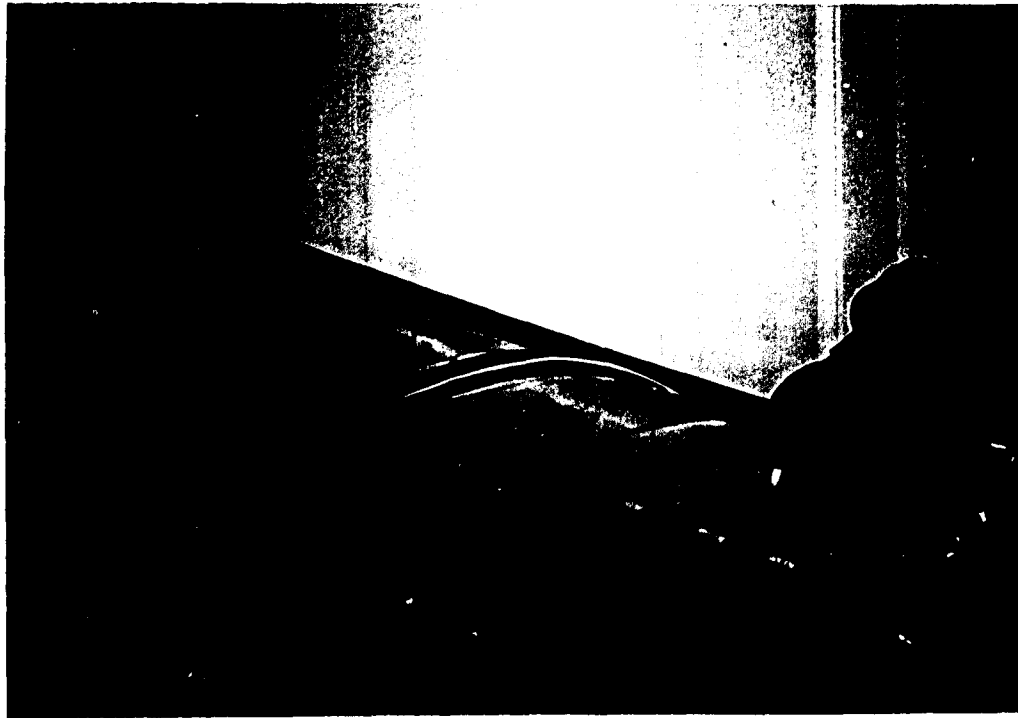


4.2.5C LEVEL WIND RELIABILITY

This consistency test was conducted repeatably using a 50 foot length of .64 inch diameter hose.

4.3 HIGH HELIX GUIDE TUBE MANUFACTURE TEST

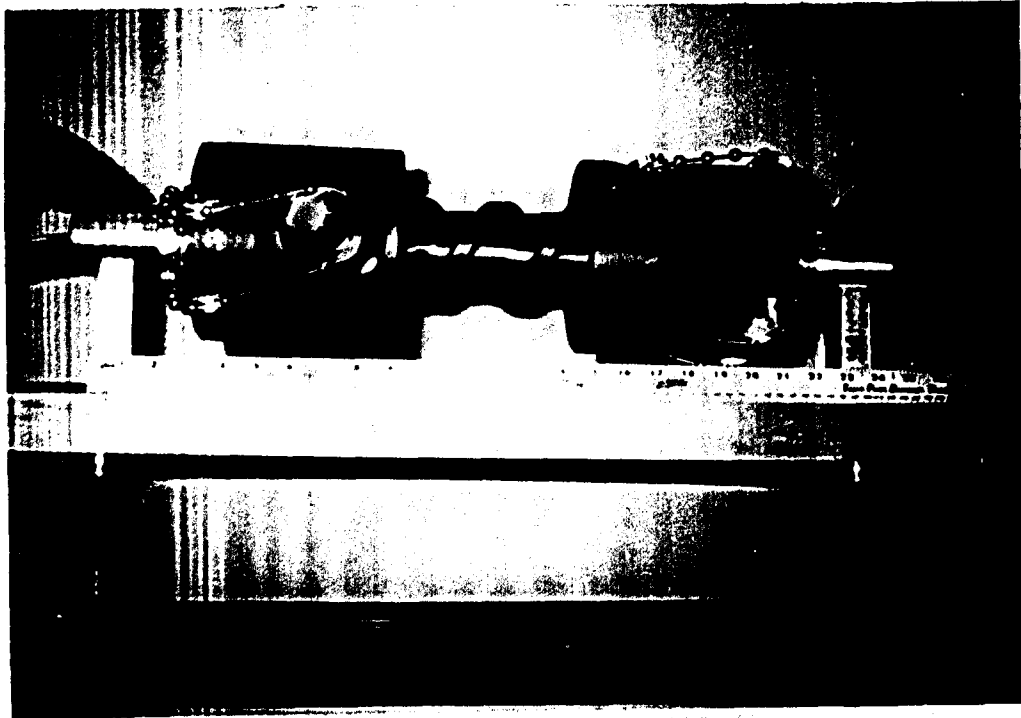
In order to feed an 11/16 inch diameter simulated array in a 10 to 16 inch diameter drum, we increased the guide tube helix angle from 27.5 degrees as proposed to 53.3 degrees. Originally, we proposed using a section of our existing 27.5 degree drive, shown in Photo 4.3A, for the AUV return guide tube.



4.3A 27.5 DEGREE GUIDE TUBE DRIVE

Phase 1 calculations indicated that the belt wrap angle would have to be increased from 11 degrees (previous standard) to 20 degrees, which caused the guide helix to also increase. As this is an exploratory study of the application of linear drive principles to establish size and weight as well as function, we ventured into this untried area of high helix cam generation. We do have mathematical formulae which defines this surface, so we chose to use a point-to-point plunge cut technique to verify manufacture. This manufacture study of guide tube helix generation was performed on a heavy duty knee mill.

Our first attempt to generate a variable 66 degree cam surface was accomplished by adjusting five axes simultaneously using plunge cuts for the actual material removal. This first method failed with sometimes half the previous cut removed by successive cuts. We then repeated the test with a 15 degree tapered mill which cured the backcutting, but caused overcuts (leading edge). The guide tube in the model used three axis control and represents our third try, with a constant 53.3 degree cam angle. The cam angle approached calculated values except for a three degree cutter undercut which may be correctable by tool tip relief. It can be seen on the model, Photo 4.3B, how this three degrees causes the belt to tend to one side rather than the center of the helically cammed surface.



4.3B ENLINE™ CAPSTAN MODEL

Looking back at Photo 4.3A, you can see how not only the belt centers on the 27.5 degree helically cammed surface, but the rope riding on the belt centers itself as well. This photo is a simulation of how the belt actually tracked under speed and load. Since we do have this cammed surface mathematically defined, we are attempting to locate computer aided design (CAD) software that can help define this high helix angle tool tip relief geometry. We presently are using AutoCad version 9.0, but their latest release (version 11.0) does not define helical geometry either. Other CAD software such as PROTOOL or third party software may hold the answers we need to define the tooling interface. We can write our own program to define geometry, if necessary.

We do believe this third method of machining, though not yet perfected, has a high probability of success. Since the guide tube helix is a function of array and stowage reel size, 53.3 degrees most likely exceeds actual requirements. We do not consider helix manufacture a design impasse, since we have successfully generated the 27.5 degree helix.

A fourth method, using a ball end mill with point-to-point CNC control would definitely work since we have mathematical definition. This method was not approached first because of time and cost constraints. The guide tube pictured, took 1600 plunge cuts to generate the surface, so

trial and error cannot be considered a method of determining a solution.

4.4 ENLINE™ CAPSTAN MODEL DESIGN VERIFICATION TEST

It was our original Phase I intent to modify existing hardware to test internal drum stowage. Because of the functional importance of the high helix angle, we modified our plan to test a helix angle nearer to that dictated by realistic stowage drum and drive size. Guide tube manufacturing constraints limited our model completion. The model, though limited in function, does offer the capability to compare calculated versus actual performance. It was our purpose to verify that a high helix angle ENLINE™ Capstan is, in fact, designable and capable of driving in a specific manner.

To verify this fact, we assembled our model with the 53.3 degree guide tube discussed in Section 4.3. The model, Photo 4.3B, was rotatable but only for limited distances (not fifty feet) because the belt was rubbing on the guide tube sidewalls. A 5/8 inch diameter by 3 foot long bar was inserted in the center of the drive, and its travel and twist compared to theoretical projections. Using this limited travel model, constants measured compared to calculations. The model did function as originally calculated as has the lower helix models. Eventually, the external drive belts would be replaced by a special gear set for a final design. A motor of any type can be used to drive the capstan around its longitudinal axis.

5.0 TECHNICAL FEASIBILITY CONCLUSIONS

Our Phase I concept study set out to investigate the feasibility of stowing an array internally on a fixed drum and to explore the application of linear drive principles for the primary drive.

Midway in the study, we realized that stowage drum and array size dictated a change in our design and test approach. It was learned that a greater guide tube helix angle was necessary to honestly evaluate an AUV sized linear drive. Because of this most important finding, we had to modify our program direction to study the likelihood of manufacturing a 53.3 degree helix compared to the existing 27.5 degree helix proposed guide tube. We believe this change of direction had proven necessary and fruitful, since manufacturing problems were encountered and solutions evolved. Because of time constraints, we have not reached a total solution nor operationally tested the drive and stowage drum combination.

More important, we have functionally verified that a high helix drive for AUV fixed drum stowage is designable. It is our contention that inherent design features of an ENLINE™ Capstan are necessary to maintain the low weight

and size to power ratios required for an AUV application, and that orderly internal fixed drum stowage is probable.

5.1 LINEAR CAPSTAN CONCLUSIONS

In order to minimize weight and size of a array deployment system, one must design a mechanism which is multipurpose for function and closed loop for control.

The ENLINETM Capstan is such a device and may be the only device capable of all functions in one operational package. The ENLINETM Capstan is a takeoff from a capstan inversion where the array becomes the capstan drum and the cable (belts) becomes the driver, see Drawing 5.1A.

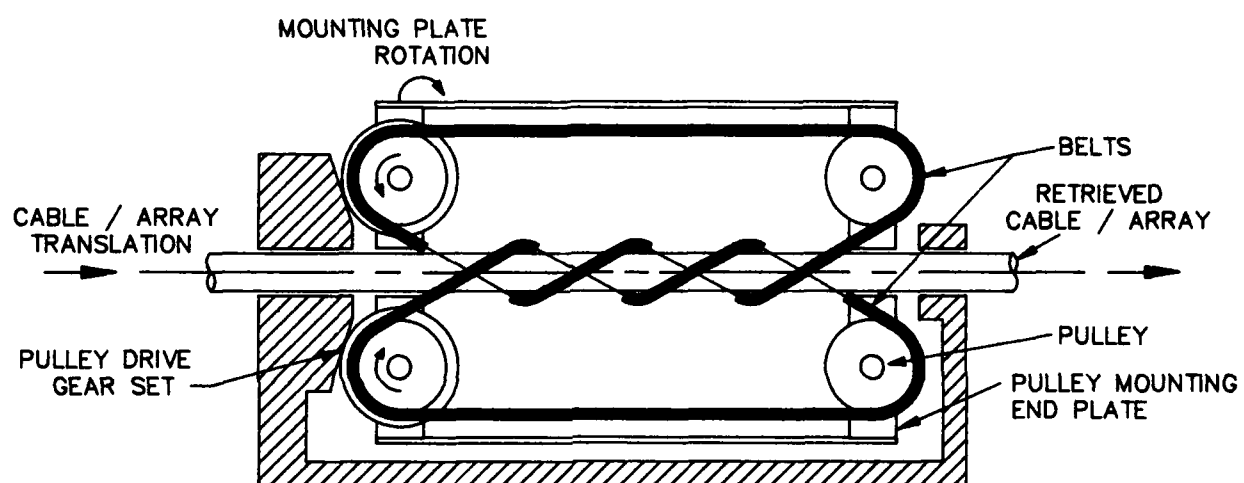
It can be seen how the belts are wrapped around the cable/array. As these belts are driven, the cable/array translates and rotates as determined by the helix angle. The belt drive pulleys are mounted on an end plate which rotates in an opposite direction of the helix to cancel cable/array rotation. This counter rotation is controlled by the fixed sun gear which drives the pulleys.

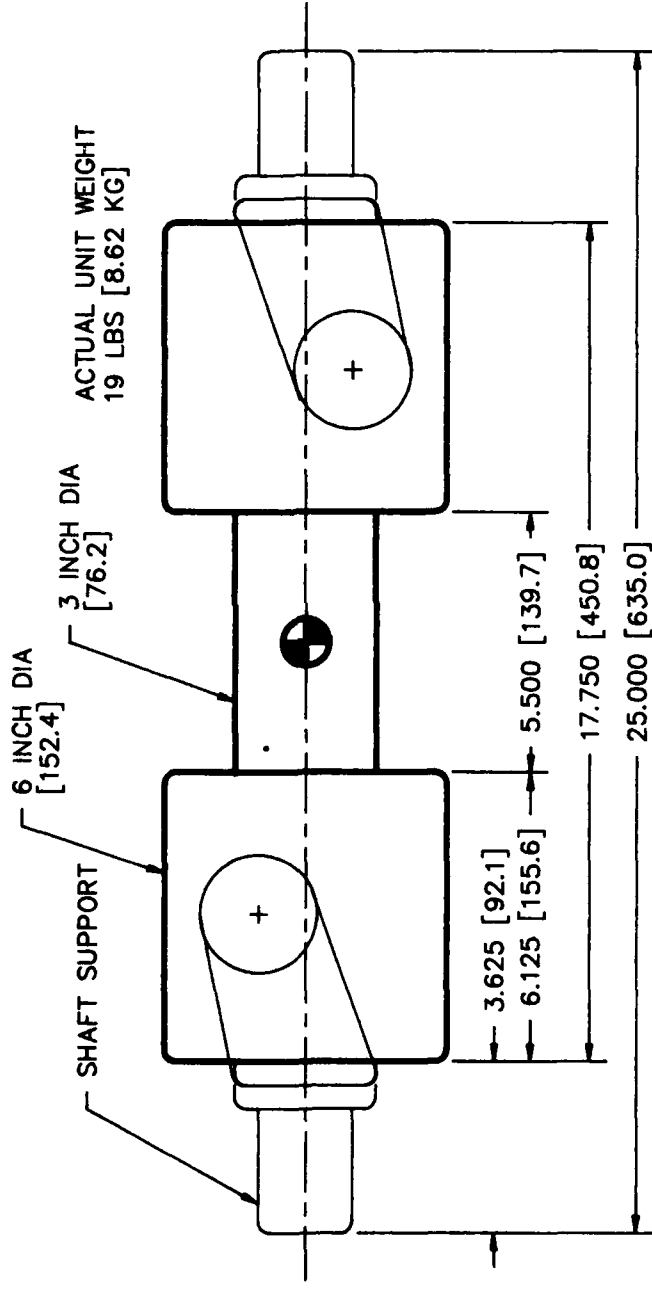
It is this separation of translation and torsional control that can make internal drum stowage possible. Our tests have shown that the model's torsional and translational components were as calculated, and are as required for fixed drum stowage. We believe the drive would be capable of low speed and force wrapping of hose as simulated in our bottle test. The model was not finalized because of the time and dollar constraints to manufacture the guide tube, which originally was not part of our Phase I proposal, but became necessary.

A device of this type has many advantages for an AUV installation:

- o It will pull a cable with a capstan force multiplier.
- o It does not require back tension and can push a cable.
- o It can push one part of the cable (stowage end) while pulling its counterpart (tow point).
- o It can be designed to apply torque or balance cable torque.
- o Its diameter to length ratio is small and its weight can be low, see Drawing 5.1B.
- o A fixed drum stowage reel does not require a rotary joint.
- o A fixed drum stowage reel may not require additional structure or mechanism.

NEXT	ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVED
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NEXT ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVED
 <p> 6 INCH DIA [152.4] 3 INCH DIA [76.2] ACTUAL UNIT WEIGHT 19 LBS [8.62 KG] SHAFT SUPPORT </p> <p> 3.625 [92.1] 6.125 [155.6] 5.500 [139.7] 17.750 [450.8] 25.000 [635.0] </p>					

The ENLINETTM Capstan is a small package that has the potential of pushing for stowage, while pulling for retrieval with closed loop torsional control. The tests conducted during Phase I show the need to develop a better method of manufacture of the guide tube helical cam. This cam surface is mathematically defined and has been manufactured at a lower helix angle. High helix manufacture would be possible using more exacting software and automated machine control. The helical guide tube manufacturing method must be further investigated for the proper array and stowage drum size.

Our Phase I ultimate design projections for Phase III were:

- o Drive Weight 50 lbs [23 KG] plus motor
- o Drive Size 7 inch [180 MM] diameter
- o Array Diameter 1 inch [25 MM] diameter
- o Array Length 200 feet [61 M]

Our Phase I accomplishments are:

- o Drive Weight * 19 lbs [8.6 kg] plus motor
- o Drive Size 6 inch [152 mm] diameter
- o Array Diameter .640 hose [16 mm] diameter
- o Array Stowage (Manual) 50 feet [15 m]

- * Drive weight may vary slightly upon completion of the final guide tube design.

Preliminary Functional Specification

- Maximum Retrieval Speed ** 100 ft/min [30 m/min]
- Maximum Retrieval Tension ** 200 lbs
- Maximum Cable Stowage *** 5/8 inch dia x 100 ft lg
1/4 inch dia x 200 ft lg
- ENLINETTM Capstan Weight (w/o motor) 15 lbs [7 kg]
- ENLINETTM Capstan Size 6 inch dia x 24 inch lg

** Dependent on motor horsepower (2 hp required).

*** Dependent on stowage drum size.

5.2 SIMULATED ARRAY STOWAGE CONCLUSIONS

In order to consider fixed drum stowage, we must be assured that cable/array will statically level wind within a container. When stowed manually, the simulated array was found to reliably level wind under a normal push force without operator induced torsional variation or visual feedback. We believe this criteria was met in that a randomly coiled cable was neatly coiled in a container by supplying only axial push. The variation of push force or random helical twist variation exceeded anticipated drive control, but still did not hinder a good level wind. Successive deploy/retrieval cycles did not cause level wind degradation. The ENLINETTM Capstan should have a more controllable feeding action with similar level wind results.

It was interesting to learn that a second elliptical layer within the first circular layer is a normal tendency. It is our belief that other internal wrapping factors can be design controllable.

These factors include:

- o Longitudinal and Torsional Stiffness
- o Array to Stowage Drum Friction
- o Stowage versus Array Diameter
- o Gravity and Acceleration Forces
- o Level Wind Type

Cable size and stiffness, the stowage drum size, and the cable drive must be a matched design.

5.3 TECHNICAL STUDY CONCLUSIONS

We have found no published data concerning a towed array from a tethered torpedo or autonomous underwater vehicle. This has been very surprising because of the usefulness of such a device. We have met with enthusiastic response and interest from all Government, commercial and news agency contacts. We believe this indicates a program for such a device does exist or should exist. We did not meet our expectation of defining an array diameter, scope and material to verify actual stowage capability. We did exceed our expectation of the high interest level which may indicate this is a patentable application and has Phase III potential.

6.0 RECOMMENDATIONS

Recent capstan techniques conceived by the principal investigator may be applied to expand present surveillance capability. These techniques may be applied to operationally deploy and retrieve an array from a torpedo shape without appreciably increasing payload. The Phase I study indicated that internal stowage of an array in a fixed drum is highly probable using ENLINETM Capstan principles. The capstan's closed loop feedback for torsional control, as well as simultaneous push/pull force are the essentials that make fixed drum stowage possible.

It is recommended that this research be continued to model a system for a specific array, investigate manufacturing techniques, then build and test the model to maximum cable stowage scope.

Product Planning Inc does intend to request gap funding from the State of Illinois to maintain project momentum. A Phase II proposal will be submitted immediately which outlines the proposed program.

AUV ARRAY DEPLOYMENT SYSTEM
PHASE I STUDY

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